

Magnetic field geometry of the large globule CB 34

A. Das • H. S. Das • Biman J. Medhi • S. Wolf

Abstract We report the results of optical polarimetric observations of a Bok globule CB34 to study magnetic field structure on large scales ($10^5 - 10^6$ AU), which is combined with archival sub-mm observations to characterize the magnetic field structure of CB34 on small scales ($10^4 - 10^5$ AU). The optical polarization measurements indicate that the magnetic field in the globule is constrained to a maximum radius of 10^5 AU around the core, out to densities not smaller than 10^4 cm^{-3} . Our study is mainly concentrated on two submillimeter cores C1 and C2 of CB34. The direction of magnetic field of core C2 is found to be nearly perpendicular to the CO outflow direction of the globule. The magnetic field of core C1 is almost aligned with the minor axis of the core which is typical for magnetically dominated star formation models. The mean value of offset between the minor axis of core C2 and the outflow direction is found to be 14° which suggests that the direction of the outflow is almost aligned with the minor axis of core C2. The magnetic field strength in the plane-of-sky for cores C1 and C2 is estimated to be $\approx 34 \mu\text{G}$ and $\approx 70 \mu\text{G}$.

Keywords ISM: clouds – polarization – ISM: magnetic fields

A. Das

Department of Physics, Assam University, Silchar 788011, India.

H. S. Das

Department of Physics, Assam University, Silchar 788011, India.

Biman J. Medhi

Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital 263129, India

S. Wolf

University of Kiel, Institute of Theoretical Physics and Astrophysics, Leibnizstr. 15, 24118 Kiel, Germany

1 Introduction

Bok globules are ideal sites for low mass star formation and the study of these objects can explore information about the earlier processes of star formation. The molecular clouds show structures on a variety of length scales, which are subdivided into *clumps*, observed in CO. These clumps have characteristic masses $10^3 - 10^4 M_\odot$, radii 2–5 parsec, temperature of 10 K, mean number density of H_2 of $10^2 - 10^3 \text{ cm}^{-3}$ and magnetic field $3 \times 10^{-5} \text{ G}$. Higher-density cloud *cores* are embedded in the clumps, observed in NH_3 , CS, and other molecules. The typical sizes are 0.05–0.1 pc, the temperature 10 K, and the density $\approx 10^4 - 10^5 \text{ cm}^{-3}$. The typical masses of core are about 1 to a few M_\odot , although a few range up to $1000 M_\odot$. The clumps are surrounded by a low density *envelope* which have a typical dimension of $\approx 10^4 - 10^6$ AU (Bodenheimer 2011).

Magnetic fields play a significant role in collapse dynamics by mediating accretion, directing the outflows and collimating jets (Li & Nakamura 2004; Galli 2009). Fields may influence the shape of cloud fragments, the contraction timescale and the gas-dust coupling (McKee & Ostriker 2007). Magnetic field maps of the molecular clouds can be derived thanks to the effect of dust grain alignment (Lazarian & Hoang 2007; Hoang & Lazarian 2014). When the light from the background stars passes through a cloud of dust grains which are aligned with their minor axis parallel to the local magnetic fields of the cloud, it becomes linearly polarized due to selective extinction. Consequently, the magnetic field can be detected through optical polarimetry in the low-density regions of molecular clouds. Complementary to this, the thermal re-emission of aligned grains located in the high-density central region of molecular clouds is linearly polarized perpendicular to the magnetic field direction and can thus be studied through submillimeter polarimetric measurement. Numerous studies have been

made on molecular clouds through optical and sub-millimeter polarimetry (Kane et al. 1995; Wolf et al. 2003; Alves et al. 2008; Ward-Thompson et al. 2009; Franco et al. 2010; Paul et al. 2012; Chakraborty et al. 2014; Bertrang et al. 2014; Chakraborty & Das 2016).

Magnetic fields are believed to play a major role in the launching and collimation mechanisms of CO outflows, so it would be interesting to study the possible relationship between the observed magnetic field directions and outflows. Ménard & Duchéne (2004) studied the alignment of T-Tauri stars with the local magnetic field which revealed a possible link between the strength of the Classical T-Tauri Star (CTTS) jets and their orientation with respect to the magnetic field. They concluded that the CTTSs with jets align to the magnetic field, but as a whole sample (i.e., both CTTSs with and without jets), the population is randomly oriented with respect to the magnetic field. Curran & Chrysostomou (2007) presented and discussed polarization maps for 16 star-forming regions, obtained with the Submillimetre Common-User Bolometer Array (SCUBA) array on the James Clerk Maxwell Telescope (JCMT) at $850\mu\text{m}$. They found no relation between mean field direction and outflow direction for the whole sample, although some alignments were noticed. Hull et al. (2014) found that the outflows are randomly aligned with B-fields, but sources with low polarization fractions showed hints of outflows being preferentially perpendicular to small-scale B-fields. Bertrang et al. (2014) reported a magnetic field orientation parallel to the CO outflow in cloud CB54, while cloud B335 shows a change in the magnetic field orientation toward the outflow axis from the inner core to the envelope regions. In CB68, they found a magnetic field orientation almost perpendicular to the CO outflow. Recently, Soam et al. (2015) studied relative orientation between magnetic field, minor axis of the cores and outflows for five dense cores IRAM 04191, L1521F, L328, L673-7 and L1014. They found that the outflows in three cores showed the alignment with the envelope magnetic field.

CB34 is a unique globule which is more massive than other globules and is situated at a distance of ~ 1.5 kpc (Launhardt et al. 2010). The description of CB34 is presented in Table 1. This globule has three dense cores (Launhardt & Henning 1997; Huard et al. 2000), and is also associated with many young stars which are believed to be formed from this globule (Alves et al. 1997). The chemical age of CB34 was estimated to be more than 10^5 yr (Scappini et al. 1998). This young age is supported by the presence of a pre-main-sequence star, CB34FU, with an age of $\sim 10^6$ yr (Alves et al. 1997). Several collimated outflows including a water maser (Gómez et al. 2006) suggest the active ongoing star formation in CB34. A bipolar CO outflow

from cool gas (Yun & Clemens 1994a), optical knots of atomic emission lines from radiative shocks (Herbig-Haro objects), and H_2 infrared jets (Yun & Clemens 1994b; Khanzadyan et al. 2002) have been reported so far. The position angle of the bipolar CO outflow is -15° whose positions of the center of the outflows $\Delta\alpha$ and $\Delta\delta$ are given by $0.2'$ and $-0.4'$ (offset from the map center of CB34) (Yun & Clemens 1994a). The molecular environment of the young cluster of Class 0 YSOs located in the CB 34 was studied by Codella & Scappini (2003) through a multiline millimeter survey. They reported that the present star formation activity is centralized in the three main clumps that have sizes of ~ 0.25 pc. Codella & Scappini (2003) further found that either CB 34 is rotating, or that different parts of it are associated with different velocities.

In contrast to previous studies, CB34 is located close to the galactic plane. The well-studied magnetic field in this region of the galaxy will allow us to constrain how close to the globule the environmental magnetic field is dominating and where the magnetic field of the Bok globule is preferentially dominated by its internal field.

2 Observations

The polarimetric observations have been performed using 1.04-metre Sampurnanand telescope of Aryabhata Research Institute of observational sciencES (ARIES) near Nainital in India. The observations have been conducted on 12–13 March, 2013 and on 20 Feb, 2015. The ARIES Imaging Polarimeter (AIMPOL) has been used as a focal plane instrument, which consists of a Wollaston prism and a rotatable half-wave plate (HWP). The function of Wollaston prism is to split the incident unpolarized beam into two rectangular polarized ordinary and extraordinary components whereas HWP changes the polarization state of the light wave. The imaging has been done using a CCD camera of 1024×1024 pixels. This CCD corresponds to 1.73 arcsec per pixel with an effective field of view of about 8 arc minute diameter on the sky. The gain of the CCD is $11.98 \text{ e}^-/\text{ADU}$ whereas the read-out noise is 7.0 e^- . The seeing radius is ~ 4 arc sec. During all the phase of observations, broadband red filter ($\lambda = 630 \text{ nm}$, $\Delta\lambda=120\text{nm}$) has been used. The observational log is now presented in Table 2. The brief information about AIMPOL and data reduction procedures are discussed in Medhi et al. (2010) and Das et al. (2013).

Standard stars with high and low degree of polarization have been also observed. The polarization details of the standard stars including offset are depicted in Table 3.

Table 1 Basic properties of CB 34. Position angle of the major axis (θ_{maj}), right ascension (RA), declination (DEC), galactic longitude and latitude (l, b), position angle of the galactic plane (θ_{GP}), distance (D), position angle of outflow (θ_{out}) and source classification (SC).

θ_{maj} ($^{\circ}$)	RA(2000) (h m s)	DEC(2000) ($^{\circ}$ ' ")	(l, b) ($^{\circ}$)	θ_{GP} ($^{\circ}$)	D^{\dagger} (parsec)	θ_{out}^{\ddagger} ($^{\circ}$)	SC
90	05:47:02.4	21:00:10	(186.94, -3.83)	148.7	1500	-15	class 0

References: † [Launhardt & Henning \(1997\)](#), ‡ [Yun & Clemens \(1994a\)](#)

Table 2 Observation log.

Object ID	Name of Observatory	Exposure time (sec)	Date
CB34	ARIES, Nainital	600	March 12–13, 2013
	ARIES, Nainital	600	Feb 20, 2015

The linear polarization (p) and position angle of the polarization vector (θ) in terms of the normalized stoke's parameters $q = Q/I$ and $u = U/I$ is given by

$$p = \sqrt{q^2 + u^2} \quad \text{and} \quad \theta = 0.5 \tan^{-1}(u/q) \quad (1)$$

3 Geometry of magnetic field

3.1 Optical polarization

The optical polarization percentage of all stars including position angles of polarization are calculated using equation (1) and is presented in Table 4. In Fig. 1a, we have over plotted the polarization vectors of observed field stars on DSS R-band image of CB 34. We considered 36 stars whose $p/E_p \geq 3$, where E_p is the error in polarization. It is to be noted that $I/E_I > 15$, where E_I is the error in intensity. The mean value of polarization of 36 stars is $p_{avg} = 2.30\%$ with a standard deviation $\sigma_p = 1.23\%$, also the mean value of position angle is $\theta_{avg} = 143.3^{\circ}$ with a standard deviation of $\sigma_{\theta} = 7.7^{\circ}$. It is also noticed from Table 4 that the star # 34 having $p = 7.61 \pm 2.27$ (in %) and $\theta = 147.0 \pm 8.6$ (in degrees), is highly polarized in comparison to p_{avg} for rest of stars although it is almost aligned with rest of stars. If we exclude this star, the mean value of polarization and position angle for the rest 35 stars are $\langle p^{opt} \rangle = 2.14\%$ and $\langle \theta^{opt} \rangle = 143.2^{\circ}$ with a standard deviation of $\sigma_p = 0.84\%$ and $\sigma_{\theta} = 7.8^{\circ}$ respectively. In Fig. 2, the distribution of degree of linear polarization and polarization position angle versus number of stars for CB 34 are plotted. The histogram for CB34 shows narrow peak close to the mean polarization direction which is usually observed in the Galactic molecular clouds.

Star # 28, located in the southern region of projected image of CB34, is the nearest field star to CB34 which is traced at optical wavelength, having limiting distance $102''$ (corresponding to $\approx 1.5 \times 10^5$ AU from the center of globule). Constraints on the impact of the large-scale ambient magnetic field on the local magnetic field structure of the Bok globule can therefore be traced as close as to this distance.

3.2 Submillimeter polarization

The sub-mm polarization data of CB34 is taken from the [Matthews et al. \(2009\)](#) legacy data set. The sub-millimeter observation of CB34 were made at the James Clerk Maxwell Telescope (JCMT), Mauna Kea, Hawaii, using the Submillimeter Common User Bolometer Array (SCUBA). The polarization data were sampled at a $10''$ pixel grid in J2000 coordinates. [Matthews et al. \(2009\)](#) selected only those measurements for which $I > 0$, $p/E_p > 2$ and $E_p < 4\%$. This criteria restricted the data points to only six (five data points are associated with core C1 and one data with core C2; ref. Fig. 31 of [Matthews et al. \(2009\)](#)). To study the magnetic field properties of cores C2 and C3, we have reanalyzed the data and calculated polarization vector at each pixel and use the criteria $I > 0$, $p/E_p > 2$, and $E_p < 6\%$ (instead of $< 4\%$). It is to be noted that $I/E_I > 23$, where E_I is the error in intensity. The polarization data is now presented in Table 5. We understand this way we are considering some low polarization signal.

It is to be noted that the sub-mm polarization angles have to be rotated by 90 degrees to show the orientation of the magnetic field, for comparison with the optical polarization angles ([Wolf et al. 2003](#)). The magnetic field position angles (θ_B^{sub}) are shown in the sixth column of Table 5. The sub-mm polarization map is now

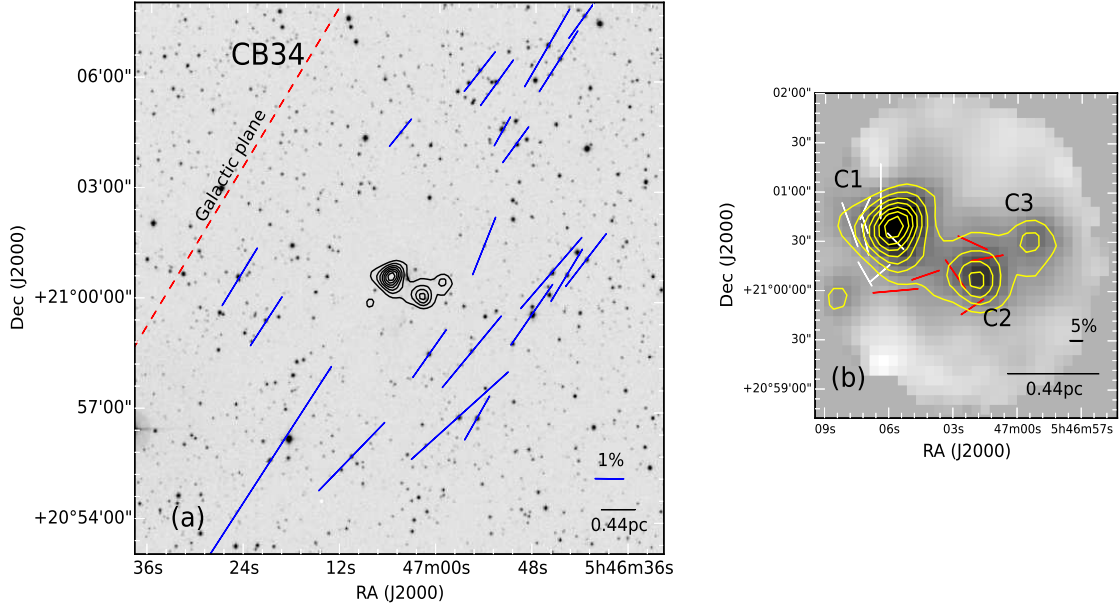


Fig. 1 (a) Optical polarization vectors (blue lines) are overplotted on a $\sim 15' \times 15'$ R-band DSS image of the field containing CB34. A vector with a polarization of 1% is drawn for reference which represents that the length of the line segments are proportional to polarization percentage. The mean value of optical polarization and position angle for stars projected in CB34 are $\langle p_{\text{opt}} \rangle = 2.14\%$ and $\langle \theta_{\text{opt}} \rangle = 143.2^\circ$ with a standard deviation of $\sigma_p = 0.84\%$ and $\sigma_\theta = 7.8^\circ$, respectively. The red dashed line represents the direction of the Galactic plane at the latitude of the cloud ($\theta_{\text{GP}} \sim 149^\circ$). Contours correspond to SCUBA $850\mu\text{m}$ dust continuum emissions which range from 0.1 to 0.7 Jy beam^{-1} in steps of 0.1 Jy beam^{-1} (Di Francesco et al. 2008). (b) Three sub-mm cores C1, C2 and C3 of CB34 are shown. Contours range from 0.1 to 0.7 Jy beam^{-1} in steps of 0.1 Jy beam^{-1} . Sub millimeter polarization vectors ($850\mu\text{m}$) are sampled on a $10''$ grid. The sub-mm data, collected from the Matthews et al. (2009) legacy data set, have been reanalyzed and presented in Table 5. Vectors are plotted where $I > 0$, $p/E_p > 2$ and $E_p < 6\%$. White and red lines are vectors associated with C1 and C2 respectively. A vector with a polarization of 5% is drawn for reference which represents that the length of the line segments are proportional to polarization percentage. The sub-mm polarization angles are rotated by 90 degrees to show the orientation of the magnetic field, for comparison with the optical polarization angles. The mean value of sub-mm polarization ($\langle p^{\text{sub}} \rangle$) and the magnetic field position angle ($\langle \theta_{\text{B}}^{\text{sub}} \rangle$) with corresponding standard deviations of core C1 are given by $12.0 \pm 6.9\%$ and $65.4 \pm 69.3^\circ$. The values for C2 are given by $13.2 \pm 3.5\%$ and $88.3 \pm 33.5^\circ$. The intensity-weighted average magnetic field position angle ($\langle \theta_{\text{B}}^{\text{sub}} \rangle_{\text{wa}}$) for cores C1 and C2 are given by $46.7 \pm 6.5^\circ$ and $90.4 \pm 12.3^\circ$.

Table 3 Results of standard polarized and unpolarized stars at R-filter. p and θ from literature; p_{obs} and θ_{obs} from observations. Since the zero position of Half Wave Plate (HWP) is not systematically aligned with the northsouth direction, offset angle is calculated using the relation: $\theta_0 = (\theta - \theta_{obs})$.

UT date	Star	p (%)	θ ($^\circ$)	p_{obs} (%)	θ_{obs} ($^\circ$)	θ_0	Ref. for p & θ
March 12, 2013	HD251204	4.79 ± 0.4	152.9	4.79 ± 0.30	155.7 ± 1.8	-2.8°	†
	HD65583	0.01 ± 0.02	144.7 ± 30.0	0.15 ± 0.20	146.3 ± 42	-1.6°	¶
March 13, 2013	HD251204	4.79 ± 0.4	152.9	4.86 ± 0.32	154.9 ± 1.7	-2.0°	†
	HD65583	0.01 ± 0.02	144.7 ± 30.0	0.12 ± 0.18	146 ± 41	-1.3°	¶
Feb 20, 2015	HD155197	4.27 ± 0.03	102.9 ± 0.18	4.29 ± 0.4	117 ± 2.6	-14.1°	§
	HD109055	0.07 ± 0.05	70.9	0.18 ± 0.20	85.2 ± 29.8	-14.3°	‡

† <http://www.sal.wisc.edu/HPOL/tgts/HD251204.html>

‡ <http://www.sal.wisc.edu/HPOL/tgts/HD109055.html>

¶ Clayton & Martin (1981)

§ Schmidt et al. (1992)

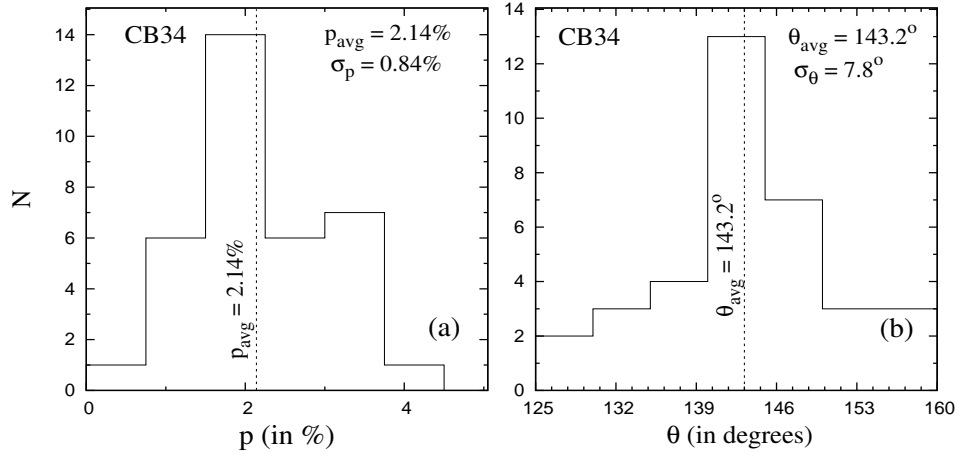


Fig. 2 Histogram shows number of star (N) versus degree of linear polarization and polarization position angle for CB 34. Dashed line in figure 2 (a) & (b) represents the position of the mean value of polarization vectors and position angle respectively for the observed field stars of CB 34 (having $p/\epsilon_p \geq 3$). We have excluded the high polarization star (# 34 of Table-4).

Table 4 Optical polarization data of CB34.

Star #	RA (2000)	DEC (2000)	p (%)	θ (°)	$p/E_p > 3$
1	05 46 28.35	21 04 30.61	0.62±0.20	143.16±9.24	Y
2	05 46 41.25	21 05 46.60	1.29±0.70	164.72±15.55	N
3	05 46 41.49	21 01 08.21	2.28±0.50	142.13±6.28	Y
4	05 46 42.03	21 07 42.99	1.77±0.56	144.11±9.06	Y
5	05 46 42.71	21 01 20.07	0.61±0.27	141.87±12.68	N
6	05 46 43.95	21 00 43.05	2.08±0.64	148.70±8.82	Y
7	05 46 44.99	21 03 24.20	1.36±1.19	156.53±25.07	N
8	05 46 45.01	21 06 33.83	2.45±0.62	147.37±7.25	Y
9	05 46 45.45	21 04 47.15	1.34±0.93	142.06±19.88	N
10	05 46 45.78	21 00 46.72	3.21±0.25	139.02±2.23	Y
11	05 46 46.51	21 06 55.07	3.06±0.25	149.67±2.34	Y
12	05 46 47.47	20 46 49.97	3.15±1.00	126.83±9.10	Y
13	05 46 47.65	21 09 49.24	1.86±0.27	150.44±4.16	Y
14	05 46 48.11	21 05 58.47	0.72±0.30	154.20±11.94	N
15	05 46 48.30	20 45 55.81	3.19±1.01	143.90±9.07	Y
16	05 46 48.31	20 59 38.99	2.51±0.70	145.24±7.99	Y
17	05 46 49.91	21 10 42.38	1.23±0.36	158.92±8.39	Y
18	05 46 50.28	21 04 14.19	1.51±0.45	143.74±8.54	Y
19	05 46 50.70	21 10 02.47	1.28±0.27	139.77±6.04	Y
20	05 46 52.19	21 04 38.60	1.13±0.26	150.50±6.59	Y
21	05 46 52.92	21 05 54.93	1.92±0.60	143.97±8.95	Y
22	05 46 54.26	21 01 29.65	2.10±0.69	158.18±9.41	Y
23	05 46 54.93	20 56 50.00	1.72±0.52	150.23±8.66	Y
24	05 46 55.03	21 06 13.28	1.72±0.50	141.61±8.33	Y
25	05 46 55.39	20 44 24.87	2.31±0.75	156.97±9.30	Y
26	05 46 55.71	20 58 38.05	3.17±1.06	140.22±9.58	Y
27	05 46 57.22	20 56 51.73	4.48±0.72	131.83±4.60	Y
28	05 47 01.00	20 58 33.42	1.99±0.63	144.77±9.07	Y
29	05 47 03.51	21 08 57.66	2.03±0.53	140.57±7.48	Y
30	05 47 04.75	21 04 31.90	1.20±0.37	140.82±8.83	Y
31	05 47 04.93	20 47 46.00	2.04±0.61	146.54±8.57	Y
32	05 47 10.62	20 55 46.02	3.25±1.01	135.76±8.90	Y
33	05 47 17.64	20 47 42.44	1.67±0.52	141.14±8.92	Y
34	05 47 20.62	20 55 38.76	7.61±2.27	146.99±8.55	Y
35	05 47 21.34	20 59 24.98	1.99±0.51	146.89±7.34	Y
36	05 47 22.18	20 42 57.48	2.36±0.65	132.23±7.89	Y
37	05 47 24.81	21 00 36.62	2.30±0.76	148.40±9.47	Y
38	05 47 25.03	20 42 51.11	3.72±1.15	130.10±8.86	Y
39	05 47 29.10	20 48 29.04	1.12±0.33	136.21±8.44	Y
40	05 47 40.25	20 48 47.60	1.50±0.50	128.14±9.55	Y
41	05 47 41.30	20 49 57.56	1.23±0.38	142.08±8.85	Y

Note: Y: Yes, N: No

presented in Fig. 1b. This map shows almost randomly oriented magnetic field directions spread over the two brightest cores in the globule, and fields in these two cores appear to be unrelated to each other. It is further noticed that the magnetic field vectors are associated with two cores (C1 and C2) only, not with core C3. So we will study the magnetic field geometry of two separate cores C1 and C2. In Fig. 1b, white and red lines are drawn to represent magnetic field vectors of two cores C1 and C2 respectively. We assume that the alignment of these field vectors are due to local magnetic field of individual core. The mean polarization ($\langle p^{\text{sub}} \rangle$) and mean position angle ($\langle \theta^{\text{sub}} \rangle$) of core C1 along with standard deviations are given by $12.0 \pm 6.91\%$ and $-24.63 \pm 69.30^\circ$ (or $155.37 \pm 69.30^\circ$). The values for C2 are given by $13.18 \pm 3.46\%$ and $-1.72 \pm 33.52^\circ$ (or $178.28 \pm 33.52^\circ$). We find that the standard deviations of $\langle p^{\text{sub}} \rangle$ and $\langle \theta^{\text{sub}} \rangle$ for core C2 are less as compared to core C1. To study average magnetic field orientations, it would be good to perform a signal-to-noise-weighted angle average so that the average orientation is weighted in favor of the detections with the highest signal-to-noise ratio (SNR). The intensity-weighted average position angle¹ ($\langle \theta^{\text{sub}} \rangle_{\text{wa}}$) for cores C1 and C2 are given by $-43.3 \pm 6.5^\circ$ (or $46.7 \pm 6.5^\circ$) and $0.4 \pm 12.3^\circ$ (or $90.4 \pm 12.3^\circ$). Also, the weighted standard deviation of position angle ($\sigma_\theta^{\text{wt}}$) for cores C1 and C2 are estimated to be 51.9° and 25.5° . In Fig. 3, the distribution of degree of linear polarization and polarization position angle for two cores (C1 and C2) of CB 34 are plotted.

We now estimate core FWHM dimensions and position angle of the minor axis (θ_{min}) of C1 and C2 from 850 μm map of CB34, which are given by ($\sim 36'' \times 33''$, $\sim 61^\circ \pm 5^\circ$) and ($\sim 35'' \times 32''$, $\sim -1^\circ \pm 5^\circ$).

The furthest sub-mm polarization vector (#1 of core C1, see Table 5) of CB34 is located $85''$ ($\approx 1.3 \times 10^5 \text{AU}$) away from the center of this globule. Thus the magnetic field at sub-mm wavelength can not be detected beyond $1.3 \times 10^5 \text{AU}$. In the Southern region, the spatial gap between polarization vectors in the sub-mm and optical is $82''$ ($\approx 1.2 \times 10^5 \text{AU}$) whereas this gap in the Western region is $120''$ ($\approx 1.8 \times 10^5 \text{AU}$).

3.3 Relative orientation between magnetic field and the Galactic plane

The mean value of position angle of polarization (optical) and standard deviation for observed field stars are $\langle \theta^{\text{opt}} \rangle \sim 143.2^\circ$ and $\sigma_\theta \sim 7.8^\circ$. The position angle of

Galactic plane at the latitude of CB 34 is $\theta_{GP} \sim 148.7^\circ$ and $|\theta_{GP} - \langle \theta^{\text{opt}} \rangle| \sim 5.5^\circ$. This suggests that the magnetic field in the periphery of CB34 is well aligned with the Galactic magnetic field in the observed plane of the sky, i.e., magnetic field in the projected plane of CB34 appears to be coupled with the Galactic magnetic field. This type of orientation is mostly pronounced at low galactic latitude like that of CB34 ($b = -3.83^\circ$). It is observed that the magnetic field within few hundred parsec of the Sun largely lies in the plane of the Galaxy (Mathewson & Ford 1970). However, Stephens et al. (2011) studied the effect of the Milky Way's magnetic field in star-forming regions using archival 350 μm polarization data on 52 Galactic star formation regions from the Hertz polarimeter module. They found that there is no correlation between mean polarization angle and Galactic location, i.e., the magnetic field in dense molecular clouds is decoupled from the large-scale Galactic magnetic field. The authors also commented that the cloud cores which are embedded in a diffuse medium (in an ordered Galactic magnetic field) usually have a meaningful net field that has no preferred direction within the Galaxy. It appears from our study that the magnetic field in the immediate environment (at scales $> 10^5 \text{AU}$) is dominated by the galactic magnetic field. But, the submillimeter polarization measurements show that the magnetic field direction in the dense regions of the globule is different from the galactic magnetic field direction.

However, the minor axes of the two cores (C1 and C2) (please see Table 7) do not show any relation to either of these directions. So, it is evident that the processes leading to the formation of the globule CB34 has not affected the ambient magnetic field to any large extent. This globule did not show pinching of the field lines or other signs that the field has been compressed due to collapse. The mean polarization angle of all field stars, then, most likely probe the average magnetic field direction of the general ISM along the line of sight to the star, and not the immediate environment of the globule.

To investigate the direction of observed polarization vectors in the peripheral region with intercloud polarization vectors, we have obtained stellar polarization data of stars from Heiles (2000) within a circular area of radius 5° about the central coordinates of CB34. The total number of stars in that circular region is 24 which have $p/E_p > 3$. The mean and the standard deviation of polarization and position angle of polarization are estimated to be $2.46 \pm 0.04\%$ and $146 \pm 40^\circ$. It further confirms that the direction of peripheral magnetic field in CB34 is also well aligned with the intercloud magnetic field.

¹ $\langle \theta^{\text{sub}} \rangle_{\text{wa}} = \frac{\sum_{i=1}^n [\theta_i (1/E_{\theta_i}^2)]}{\sum_{i=1}^n [1/E_{\theta_i}^2]}$

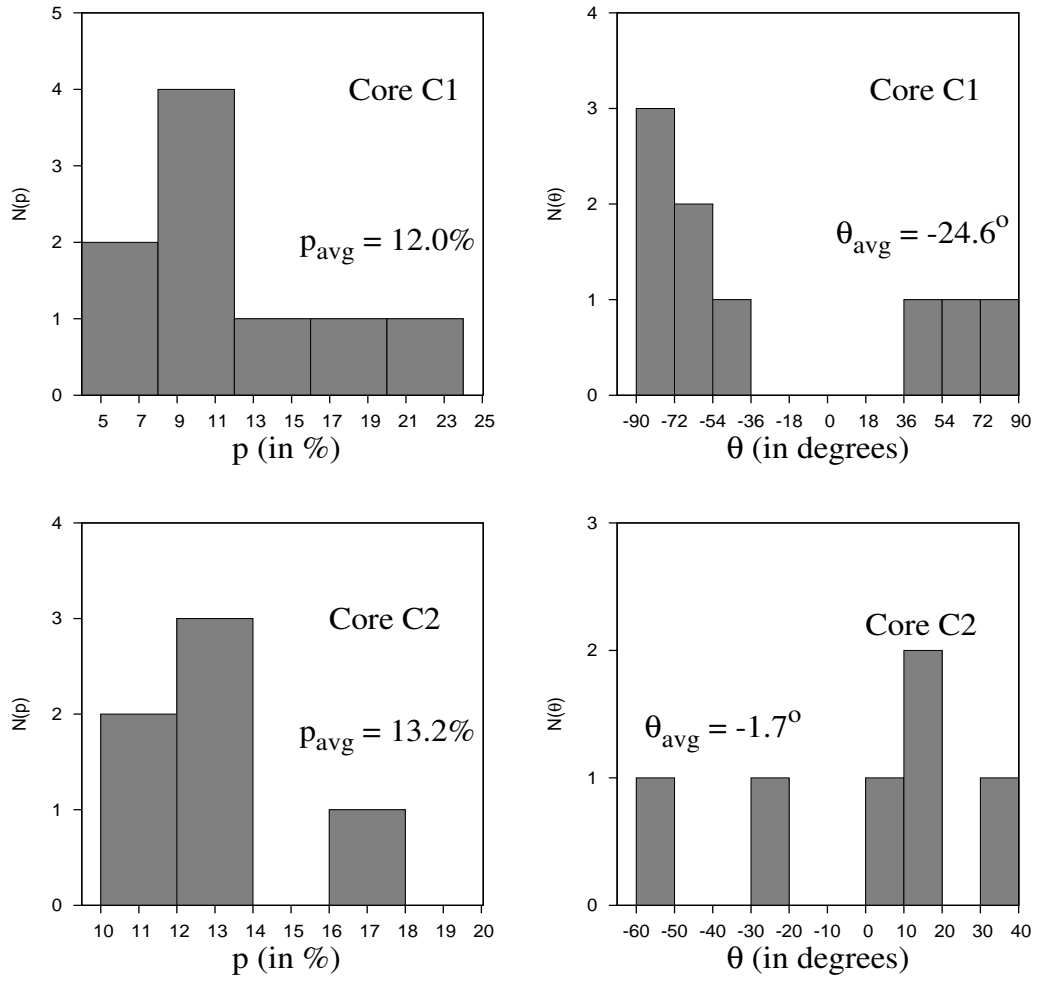


Fig. 3 Histogram shows the distribution of degree of linear polarization and polarization position angle for two cores (C1 and C2) of CB 34.

Table 5 Submm polarization data of CB34 with $I > 0$, $p/E_p > 2$ and $E_p < 6\%$. The table is created from the CADC repository of the SCUBA Polarimeter Legacy Catalogue (Matthews et al. 2009) after reanalyzing the data set. The first column represents the serial number of sub mm polarization vectors whereas the second and the third column represent pixel position of vectors in equatorial coordinate system. The fourth and fifth column are for degree of linear polarization and polarization angle of vectors. To compare with the optical polarization angles, the sub-mm polarization angles have been rotated by 90° to indicate the orientation of the magnetic field. The magnetic field position angles (θ_B^{sub}) are shown in the sixth column. In the last column, the polarization vectors associated with cores C1 and C2 are shown.

#	RA (2000)	DEC (2000)	p (%)	PA ($^\circ$)	θ_B^{sub} (= PA + 90°)	Core
1	05 47 7.8	21 00 40.2	18.79 ± 3.79	-70.78 ± 5.91	19.22	C1
2	05 47 7.1	21 00 10.2	11.04 ± 4.28	-61.02 ± 8.7	28.98	C1
3	05 47 7.1	21 00 31.2	12.93 ± 5.2	-77.43 ± 6.36	12.57	C1
4	05 47 7.1	21 00 40.2	07.30 ± 2.25	-72.08 ± 9.01	17.92	C1
5	05 47 7.1	21 00 50.2	9.76 ± 3.36	66.26 ± 9.06	156.26	C1
6	05 47 6.4	21 00 10.8	10.05 ± 4.16	42.07 ± 9.98	132.07	C1
7	05 47 6.4	21 00 50.2	6.77 ± 2.96	87.16 ± 16.2	177.16	C1
8	05 47 6.4	21 01 00.6	22.33 ± 4.55	-89.89 ± 11.31	0.11	C1
9	05 47 5.7	21 00 00.0	17.61 ± 4.58	5.43 ± 7.11	95.43	C2
10	05 47 5.7	21 00 30.2	9.02 ± 2.99	-45.97 ± 4.98	44.03	C1
11	05 47 4.3	21 00 09.6	11.37 ± 4.54	19.92 ± 10.59	109.92	C2
12	05 47 2.9	21 00 10.2	13.98 ± 4.36	-56.38 ± 10.68	33.62	C2
13	05 47 2.1	20 59 50.4	10.77 ± 5.08	35.59 ± 19.64	125.59	C2
14	05 47 2.1	21 00 29.4	12.61 ± 5.36	-25.51 ± 11.15	64.49	C2
15	05 47 1.4	21 00 20.2	12.71 ± 3.09	10.61 ± 5.48	100.61	C2

The offset angle between the Galactic plane and magnetic field of two cores (C1 and C2) are found to be 102° and 58.3° . This suggests that the inner magnetic field of CB34 is not coupled with the galactic magnetic field.

4 Mean particle density

The density structure of a star forming cloud cores is one of the most important physical quantities that explores the evolution of the protostellar collapse and its stellar end product. The mean particle density $\langle n_{H_2} \rangle$ is given by (Pereyra & Magalhães 2007)

$$\langle n_{H_2} \rangle = \langle A_V \rangle \left(\frac{N_{H_2}}{A_V} \right) \frac{1}{l} \quad cm^{-3}, \quad (2)$$

assuming it to be a cylindrical filament. Here, A_V is the extinction, N_{H_2} is the hydrogen column density and l (in cm) is the typical dimension of the cloud.

The standard gas-to-extinction ratio is given by (Bohlin et al. 1978)

$$\left(\frac{N_{H_2}}{A_V} \right) = 0.94 \times 10^{21} \quad cm^{-2} mag^{-1}, \quad (3)$$

We will now derive the mean particle density in both the high density and low density region.

4.1 High density region

Wang et al. (1995) reported N_{H_2} value for globule CB34 from $C^{18}O$ $J = 2 \rightarrow 1$ study, which is given by $9.9 \times 10^{21} cm^{-2}$. In Section 3.2, the dimension of the two cores C1 and C2 have been estimated and is given by $\sim 36''$ and $\sim 35''$. Using these data, it is possible to estimate the mean particle density at the central region of the cloud, especially at cores C1 and C2. The values are given by $1.22 \times 10^4 cm^{-3}$ and $1.26 \times 10^4 cm^{-3}$.

4.2 Low density region

Near-infrared extinction measurements can detect dust column densities in the low-density outer regions of the globules. To construct the extinction map of CB34, we have used the Near-Infrared Color Excess (NICE) method developed by Rowles & Froebrich (2009) (RF). This method was first introduced by Lada et al. (1994) which combines measurement of NIR color excess to directly estimate the extinction and to map the dust column density through a molecular cloud. In RF's method, the median color of all stars at each pixel position has to be determined. Then each median color map has to be converted into the respective color excess map so that one can determine the extinction/column density of material. We used this method earlier to construct extinction map of two globules CB224

and CB130 (Barman & Das 2015; Chakraborty & Das 2016).

We have collected the J , H and K_s magnitudes of all field stars from the 2MASS Point Source Catalog in regions of $25' \times 25'$ centered on the globule CB34 (Cutri et al. 2003), to build the extinction map. Only those stars are considered whose JHK_s magnitude show photometric quality flag of “AAA” which actually corresponds to $\text{SNR} > 10$.

The infrared color excess is related to the visual extinction via extinction law (Rowles & Froebrich 2009):

$$A_V = \frac{5.689}{2}(A_{H, <J-H>} + A_{H, <H-K_s>}), \quad (4)$$

where,

$$A_{H, <J-H>} = \frac{<J-H>}{(\frac{\lambda_H}{\lambda_J})^\beta - 1} \text{ or } A_{H, <H-K_s>} = \frac{<H-K_s>}{1 - (\frac{\lambda_{K_s}}{\lambda_H})^{-\beta}}$$

is the extinction in the H-band. Here, $<J-H>$ and $<H-K_s>$ are the color excess.

Rowles & Froebrich (2009) used the value of $\beta = 1.7$, since previous studies show that it lies between 1.6 and 2.0 (Martin et al. 1990; Draine 2003). To derive extinction from equation (4), we have also taken $\beta = 1.7$. The visual extinction map of CB34 is now shown in Fig. 4. The field of view of visual extinction map is $\sim 25' \times 25'$, having dimension of each pixel = $10'' \times 10''$ (spatial resolution = $34''$).

The average extinction in the low density region can be estimated which is given by ≈ 1.80 mag. The closest star which is traceable in the low density region is located at $\approx 100''$ from the center of globule. Thus we can determine the mean particle density using equation (2), considering the cloud dimension of $\approx 200''$, which is given by $3.76 \times 10^2 \text{ cm}^{-3}$. The hydrogen column densities (N_{H_2}) for the region traced by optical observations can be calculated using equation (3) and is given by $1.7 \times 10^{21} \text{ cm}^{-2}$.

5 Magnetic field strength

We will now estimate the magnetic field strength (in Gauss) for SCUBA data using the relation (Chandrasekhar & Fermi 1953):

$$B = |B_{POS}| = \sqrt{\frac{4\pi}{3}\rho_{\text{gas}}} \frac{v_{\text{turb}}}{\sigma_\theta}, \quad (5)$$

where ρ_{gas} is the gas density (in g cm^{-3}), v_{turb} is the rms turbulence velocity (cm s^{-1}), and σ_θ is the standard deviation of the polarization position angles

in radians. It is also assumed that the magnetic field is frozen in the cloud material.

The total gas density ρ_{gas} is given by (Henning et al. 1997)

$$\rho_{\text{gas}} = 1.36 n_{H_2} M_{H_2}, \quad (6)$$

where $M_{H_2} = 2.0158 \text{ amu} = 2.0158 \times 1.66 \times 10^{-24} \text{ g}$ is the mass of a H_2 molecule.

The rms turbulence velocity (v_{turb}) is given by (Wang et al. 1995)

$$v_{\text{turb}} = \frac{\Delta v}{2.35}, \quad (7)$$

where Δv is the FWHM line width, measured at quiescent positions located away from the emission peaks.

The mean density (n_{H_2}) of two cores and FWHM line width of CB34 are given by $1.2 \times 10^4 \text{ cm}^{-3}$ and 1.5 kms^{-1} (Wang et al. 1995). We have estimated the mean magnetic field strength of two cores C1 and C2 using the formulae mentioned above, where weighted standard deviation of position angle (σ_θ^{wt}) of two cores is considered. The results are presented in Table 6. The magnetic field in core C2 is $\approx 70 \mu\text{G}$, which is more by a factor of 2, than the estimated field strength of core C1 $\approx 34 \mu\text{G}$. It is observed that the sub-mm polarization vectors in core C1 are oriented more randomly than core C2. Codella & Scappini (2003), through multiline millimetre survey, reported that the current star forming activity in CB34 is concentrated in the three main clumps. They found that either CB34 is rotating, or that different parts of it are associated with different velocities. This may be the reason why the polarization vectors are not ordered at the core of CB 34.

6 Discussion

6.1 Correlation between magnetic field and outflows

Magnetic fields in a cloud play a notable role in the collapse of cloud and the formation of circumstellar disks and outflows. Matsumoto & Tomisaka (2004) and Matsumoto et al. (2006) showed that the alignment between the magnetic field and outflow depends on the magnetic field strength, i.e., the alignment will be better when the magnetic field is stronger. This result is based on MHD simulations on a slowly rotating globule core which is undergoing gravitational collapse. Curran & Chrysostomou (2007) found no relation between mean magnetic field direction and outflow direction from the study of 16 high-mass star-

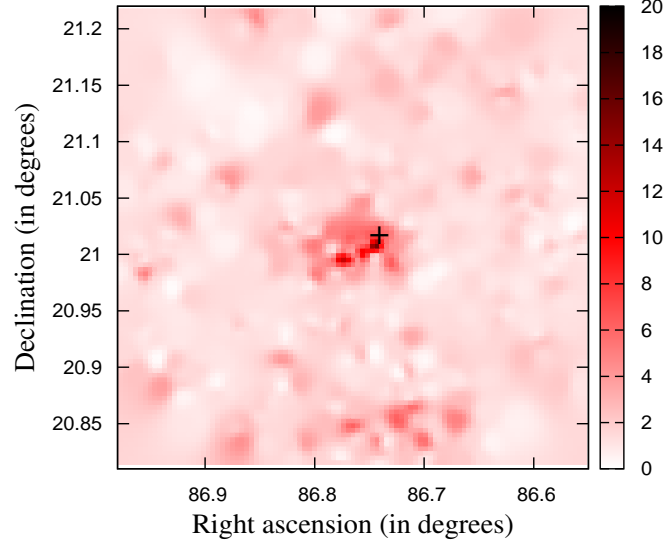


Fig. 4 Extinction map of CB34 constructed using the NICE method having field of view (FOV) $\sim 25' \times 25'$, dimension of a pixel = $10'' \times 10''$ (spatial resolution = $34''$). The '+' sign denotes the center of the globule. The color bar represents the extinction scale which is in magnitude unit.

Table 6 Position of cores, mean degree of polarization along with standard deviation, intensity-weighted average magnetic field position angle along with weighted standard deviation and magnetic field strength of two sub-mm cores C1 and C2.

Core	RA (2000)	DEC (2000)	$\langle p_{\text{sub}} \rangle$ (%)	σ_p (%)	$\langle \theta_B^{\text{sub}} \rangle_{\text{wa}}$ ($^\circ$)	$\sigma_\theta^{\text{wt}}$ ($^\circ$)	B (μG)
C1	05 47 06	21 00 41	12.00	6.91	46.7	51.9	34
C2	05 47 02	21 00 10	13.18	3.46	90.4	25.5	70

Table 7 Weighted average magnetic field position angles and angular orientations between magnetic field, core minor axis and outflows of two sub-mm cores C1 and C2 (*wa*: intensity-weighted average; *sub*: submillimetre data; *min*: minor axis of the core; *out*: outflow direction).

Core	$\langle \theta_B^{\text{sub}} \rangle_{\text{wa}}$	θ_{min}	θ_{out}	$ \langle \theta_B^{\text{sub}} \rangle_{\text{wa}} - \theta_{\text{min}} $	$ \langle \theta_B^{\text{sub}} \rangle_{\text{wa}} - \theta_{\text{out}} $	$ \theta_{\text{out}} - \theta_{\text{min}} $
C1	46.7°	61°	-15°	14.3°	61.7°	76°
C2	90.4°	-1°	-15°	91.4°	105.4°	14°

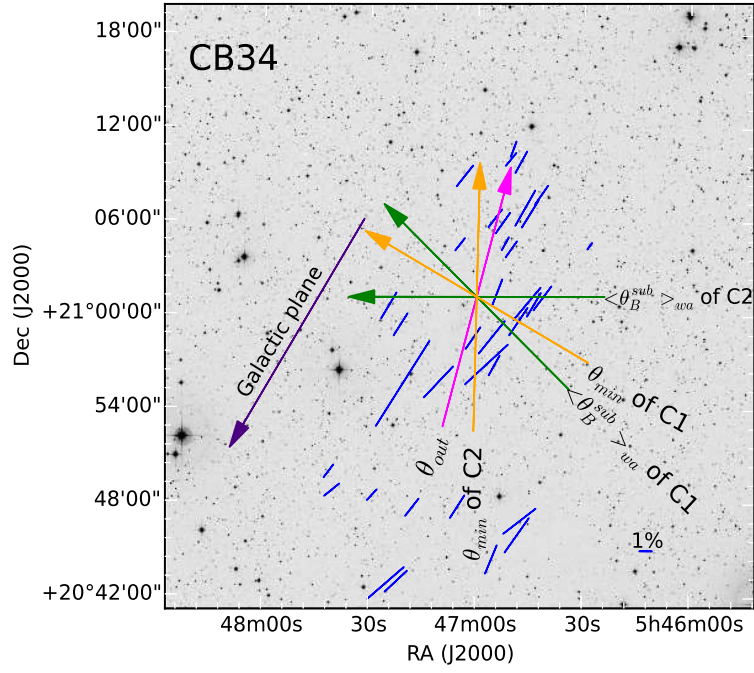


Fig. 5 Schematic diagram of CB34 showing the orientations of the intensity-weighted average magnetic field of two cores C1 and C2, minor axis (θ_{min}) of C1 and C2, direction of outflow (θ_{out}), and the Galactic plane w.r.t. the north. Optical polarization vectors (blue lines) are overplotted on a large field $\sim 40' \times 40'$ R-band DSS image of the field containing CB34. A vector with a polarization of 1% is drawn for reference which represents that the length of the line segments are proportional to polarization percentage.

forming regions, although some alignments were noticed. [Hull et al. \(2014\)](#) studied the correlation of B-fields with bipolar outflows and found that the sources with low polarization fractions show hint that outflows are preferentially perpendicular to small-scale B-fields. They commented that in those sources the fields have been wrapped up toroidally by envelope rotation. Many observations have been reported to study the correlation between magnetic field and CO outflow of the Bok globules (e.g., [Cohen et al. \(1984\)](#); [Vrba et al. \(1986\)](#); [Jones & Amini \(2003\)](#); [Wolf et al. \(2003\)](#); [Hull et al. \(2013\)](#); [Bertrang et al. \(2014\)](#); [Soam et al. \(2015\)](#)). Some study shows a good alignment of globule's magnetic field with outflow axis (e.g., [Cohen et al. \(1984\)](#); [Vrba et al. \(1986\)](#); [Jones & Amini \(2003\)](#)), whereas misalignment of magnetic field direction and outflow axis have been also reported (e.g. [Wolf et al. \(2003\)](#); [Ménard & Duchéne \(2004\)](#); [Hull et al. \(2013\)](#); [Targon et al. \(2011\)](#); [Soam et al. \(2015\)](#)). [Soam et al. \(2015\)](#) reported that in IRAM 04191, the outflow is oriented almost perpendicular ($\sim 84^\circ$) to the peripheral magnetic field, but it is oriented almost parallel ($\sim 16^\circ$) to the inner magnetic field. In the case of globules B335, CB230 and CB68, the outflows are oriented almost perpendicular to the inner magnetic field ([Wolf et al. 2003](#); [Bertrang et al. 2014](#)). [Bertrang et al. \(2014\)](#) also reported that the magnetic field orientation of CB54 is aligned with CO outflow.

The position angle of the bipolar outflow (θ_{out}) of CB34 is -15° whose positions of the center of the outflows $\Delta\alpha$ and $\Delta\delta$ are given by $0.2'$ and $-0.4'$ (offset from the map center of CB34) ([Yun & Clemens 1994a](#)). Looking at the position coordinates of cores and outflow, we notice that the outflow center is very close to core C2. The angular offset between $\langle \theta_B^{sub} \rangle_{wa}$ and θ_{out} for cores C1 and C2 are respectively, 61.7° and 105.4° (c.f Table 7). Thus the outflow axis is almost perpendicular to the magnetic field orientation of core C2. Orientation of both the polarization vectors and the outflow are shown in Fig. 5.

6.2 Correlation between magnetic field, minor axis of the cores, and outflows

We have estimated the orientation of the minor axis of two cores C1 and C2 which are given by 61° and -1° . It can be seen from Table 7 that the angular offset between $\langle \theta_B^{sub} \rangle_{wa}$ and θ_{min} for C1 and C2 are 14.3° and 91.4° . Thus minor axis of the core C1 is almost aligned with inner magnetic field. This result is consistent with magnetically dominated star formation model which suggests that the magnetic field should lie along the minor axis of the molecular cloud ([Mouschovias & Morton](#)

[1991](#); [Li 1998](#)). It is also expected that the cloud tends to contract first in a direction parallel to the magnetic field and then in quasi-statically perpendicular to the field orientation ([Li 1998](#); [Ward-Thompson et al. 2009](#)). However, core C2 shows almost opposite nature where projected magnetic field vector is found to be perpendicular to the position angle of the minor axis, which is inconsistent with the above model. The mean value of offset between θ_{out} and θ_{min} for C1 and C2 are found to be 76° and 14° . This finding suggests that the the CO outflow is oriented almost parallel to the minor axis of C2. It is also to be noted that the outflow center is close to core C2 (which is already discussed in Section 5.1), so we believe this outflow may be associated with core C2. It is important to mention here is that the major and minor axes of cores C1 and C2 don't differ very much, and that the reader should take that into account when considering their results regarding magnetically-dominated versus not-magnetically-dominated star formation.

[Soam et al. \(2015\)](#) found that the angular offset between θ_B^{sub} and θ_{rot} for IRAM 04191 is 14° , i.e., inner magnetic field is almost parallel to the minor axis of the globule. In the case of IRAM 04191 and L1521F, the outflows are oriented parallel to the minor axis of the clouds. Recently, [Chapman et al. \(2013\)](#) reported the $350\mu\text{m}$ polarization observations of four low-mass cores containing Class 0 protostars: L483, L1157, L1448-IRS2 and Serp-FIR1. A strong correlation between minor axes and outflow direction was observed. They concluded that the outflow inclination angle could be used as a proxy for the pseudodisk symmetry (minor) axis inclination angle.

7 Conclusions

1. We present the optical imaging polarimetric observations of a large globule CB34 which were carried out using the Aryabhata Research Institute of observational sciencES (ARIES) Imaging Polarimeter mounted on Cassegrain focus of the 1.04m Sampurnanand Telescope of ARIES, Nainital, in R photometric band, on 12–13 March, 2013 and on 20 Feb, 2015. The mean value of optical polarization and position angle for stars projected in CB34 are $\langle p^{opt} \rangle = 2.14\%$ and $\langle \theta^{opt} \rangle = 143.2^\circ$ with a standard deviation of $\sigma_p = 0.84\%$ and $\sigma_\theta = 7.8^\circ$, respectively.

The mean polarization ($\langle p^{sub} \rangle$) and mean position angle ($\langle \theta^{sub} \rangle$) of core C1 along with standard deviations are given by $12.0 \pm 6.91\%$ and $-24.63 \pm 69.30^\circ$ (or $155.37 \pm 69.30^\circ$). The values for

- C2 are given by $13.18 \pm 3.46^\circ$ and $-1.72 \pm 33.52^\circ$ (or $178.28 \pm 33.52^\circ$). The intensity-weighted average position angle ($\langle \theta^{sub} \rangle_{wa}$) for cores C1 and C2 are given by $-43.3 \pm 6.5^\circ$ and $0.4 \pm 12.3^\circ$. Also, the weighted standard deviation of position angle (σ_θ^{wt}) for cores C1 and C2 are estimated to be 51.9° and 25.5° .
2. The direction of the magnetic field inside the dense region (traced through sub-mm polarimetry) is oriented approximately perpendicular to the magnetic field direction in the less dense outer regions of the globule. This implies that only the magnetic field in the dense regions is related to the physical processes inside the globule, while the magnetic field in the low-density region in the environment of the globule (traced through optical polarimetry) is not. The transition between the two regimes is around 10^5 AU.
 3. The magnetic field of core C2 is found to be almost perpendicular with the outflow direction of CB34 which is also observed in past for three clouds B335, CB230 and CB68 (Wolf et al. 2003; Bertrang et al. 2014). The magnetic field strength in the plane-of-sky for two cores C1 and C2 is estimated to be $B_{sub} \approx 34\mu\text{G}$ and $\approx 70\mu\text{G}$.
 4. The angular offset between intensity-weighted average magnetic field position angle of core C1 and the minor axis position angle is found to be 14.3° . This suggests that the magnetic field of core C1 is nearly aligned with the minor axis of the core. This feature is typical for magnetically dominated star formation models. We also find that the inner magnetic field of C2 is inclined at an angle of 91.4° with the minor axis of the cloud that is inconsistent with magnetically dominated star formation models. Since the major and minor axes of cores C1 and C2 don't differ very much, so one should take that into account when considering his results regarding magnetically-dominated versus not-magnetically-dominated star formation.
 5. The mean value of offset between the minor axis of the core C2 and the outflow directions is found to be 14° . Thus the direction of outflow is almost aligned with the minor axis of the core C2.

Acknowledgements

We are thankful to ARIES, Nainital for providing us the Telescope time. This work makes use of data products from the CADC repository of the SCUBA Polarimeter Legacy Catalogue and is highly acknowledged. We also acknowledge the use of the VizieR database of astronomical catalogues namely Two Micron All Sky Survey

(2MASS), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We are thankful to anonymous referee for helpful suggestions which definitely helped to improve the quality of the paper. This work is supported by the Science and Engineering Research Board (SERB), a statutory body under Department of Science and Technology (DST), Government of India, under Fast Track scheme for Young Scientist (SR/FTP/PS-092/2011).

References

- Alves J. F., Hartmann L., Bri  o C., Lada C. J., 1997, *AJ*, 113, 1395
- Alves F. O., Franco G. A. P., Girart J. M., 2008, *A&A*, 486, L13
- Barman A., Das H. S., 2015, *Asian Journal of Physics*, 24, 1045
- Bertrang G., Wolf S., Das H. S., 2014, *A&A*, 565, A94
- Bodenheimer P. H., 2011, *Principles of Star Formation* (Astronomy and Astrophysics Library. ISBN 978-3-642-15062-3. Springer-Verlag Berlin Heidelberg)
- Bohlin R. C., Savage B. D., & Drake J. F. 1978, *ApJ*, 224, 132
- Chakraborty A., Das H. S., Paul D., 2014, *MNRAS*, 442, 479
- Chakraborty A., Das H. S., 2016, *ASS*, 361, 321
- Chandrasekhar S., Fermi E., 1953, *ApJ*, 118, 113
- Chapman N. L., Davidson J. A., Goldsmith P. F., et al., 2013, *ApJ*, 770, 151
- Clayton G. C., Martin P. G., 1981, *AJ*, 86, 1518
- Clemens D. P., 2012, *ApJ*, 748, 18
- Clemens D. P., Barvainis R., 1988, *ApJS*, 68, 257
- Codella C., Scappini F., 2003, *MNRAS*, 344, 1257
- Cohen R. J., Rowland P. R., Blair M. M., 1984, *MNRAS*, 210, 425
- Cutri R. M., et al., 2003, *VizieR Online Data Catalog*, 2246, 0
- Curran R. L., Chrysostomou A., 2007, *MNRAS*, 382, 699
- Das H. S., Medhi B. J., Wolf S., Bertrang G., Deb Roy. P., Chakraborty A., 2013, *MNRAS*, 436, 3500
- Di Francesco J., Johnstone D., Kirk H., MacKenzie T., Ledwosinska E., 2008, *ApJS*, 175, 277
- Draine B. T., *ARA&A*, 2003, 41, 241
- Franco G. A. P., Alves F. O., Girart J. M., 2010, *ApJ*, 723, 146
- Galli D. 2009, *Mem. Soc. Astron. It.*, 80, 54
- G  mez J. F., de Gregorio-Monsalvo I., Suarez O., Kuiper T. B. H., 2006, *AJ*, 132, 1322
- Heiles C. 2000, *AJ*, 119, 923
- Henning T., Wof S., Launhardt R., Waters R., 1997, *ApJ*, 561, 871
- Hoang T., Lazarian A., 2014, *MNRAS*, 438, 680
- Huard, T. L., Weintraub, D. A., & Sandell, G. 2000, *A&A*, 362, 635
- Hull C. L. H., Plambeck R. L., Bolatto A. D., et al., 2013, *ApJ*, 768, 159
- Hull C. L. H., Plambeck R. L., Kwon W., Bower G. C., Carpenter J. M., Crutcher R. M., Fiege J. D., and coauthors, 2014, *ApJS*, 213, 13
- Jones T. J., Amini H., 2003, *AJ*, 125, 1418
- Kane B. D., Clemens D. P., Leach R. W., Barvainis R., 1995, *ApJ*, 445, 269
- Khanzadyan T., Smith M. D., Gredel R., Stanke T., Davis C. J., 2002, *A&A*, 383, 502
- Launhardt R., Henning T., 1997, *A&A*, 326, 329
- Lada C. J., Lada E. A., Clemens D. P., Bally J., 1994, *ApJ*, 429, 694
- Launhardt R., Nutter D., Ward-Thompson D., Bourke T. L., Henning Th., Khanzadyan T., Schmalzl M., Wolf S., Zylka R., 2010, *ApJS*, 188, 139
- Lazarian A., Hoang T., 2007, *MNRAS*, 378, 910
- Li Z. Y., 1998, *ApJ*, 493, 230.
- Li Z.-Y., Nakamura F., 2004, *ApJ*, 609, L83
- Martin P. G., Whittet D. C. B., 1990, *ApJ*, 357, 113
- Mathewson D. S., Ford V. L., 1970, *Mem. R. Astron. Soc.*, 74, 139
- Matsumoto T., Tomisaka K., 2004, *ApJ*, 616, 266
- Matsumoto T., Nakazato T., Tomisaka K., 2006, *ApJ*, 637, L105
- Matthews B. C., McPhee C. A., Fissel L. M., Curran R. L., 2009, *ApJS*, 182, 143
- McKee C. F. & Ostriker, E. C. 2007, *ARA&A*, 45, 565
- Medhi Biman J., Maheswar G., Pandey J. C., Tamura Motohide., Sagar R., 2010, *MNRAS*, 403, 1577
- M  nard F., & Duch  ne G., 2004, *A&A*, 425, 973
- Mouschovias T. Ch., Morton S. A. 1991, *ApJ*, 371, 296
- Paul D., Das H. S., Sen A. K., 2012, *BASI*, 40, 113
- Pereyra A., Magalh  es A. M., 2007, *ApJ*, 662, 1014
- Rowles J., Froebrich D., 2009, *MNRAS*, 395, 1640
- Scappini F., Cecchi-Pestellini C., Olberg M., Casolari A., Fanti C., 1998, *ApJ*, 504, 866
- Schmidt G. D., Elston R., Lupie O. L., 1992, *AJ*, 104, 1563
- Soam A., Maheswar G., Lee C. W., Dib Sami, Bhatt H. C., Tamura M., Kim G., 2015, *A&A*, 573, A34
- Stephens I. W., Looney L. W., Dowell C. D., Vaillancourt J. E., Tassis K., 2011, *ApJ*, 728, 99
- Targon C. G., Rodrigues C. V., Cerqueira A. H., Hickel G. R., 2011, *ApJ*, 743, 54
- Vrba F. J., Luginbuhl C. B., Strom S. E., Strom K. M., Heyer, M. H., 1986, *AJ*, 92, 633
- Wang Y., Evans N. J., II Zhou S., Clemens D. P., 1995, *ApJ*, 454, 217
- Ward-Thompson D., Sen A. K., Kirk J. M., Nutter D., 2009, *MNRAS*, 398, 394
- Wolf S., Launhardt R., Henning T., 2003, *ApJ*, 592, 233
- Yun J. L., Clemens D. P., 1994a, *ApJS*, 92, 145
- Yun J. L., Clemens D. P., 1994b, *AJ*, 108, 612